

cones at the time of initial contact. For this purpose, the mating surfaces of the drive cones are coated with dry lubricant films. In addition, the ball-bearing assembly contains a reservoir designed to dispense lubricant to support an elastohydrodynamic film for the specified lifetime of the system.

*This work was done by Edward P. Kingsbury, Robert Price, Erik Gelotte, and Herbert B. Singer of The Bearing Consultants, LLP for Glenn Research Center. Further information is contained in a TSP (see page 1).*

*Inquiries concerning rights for the commercial use of this invention should be ad-*

*ressed to NASA Glenn Research Center, Commercial Technology Office, Attn: Steve Fedor, Mail Stop 4-8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17282.*

## ❁ Flux-Based Deadbeat Control of Induction-Motor Torque

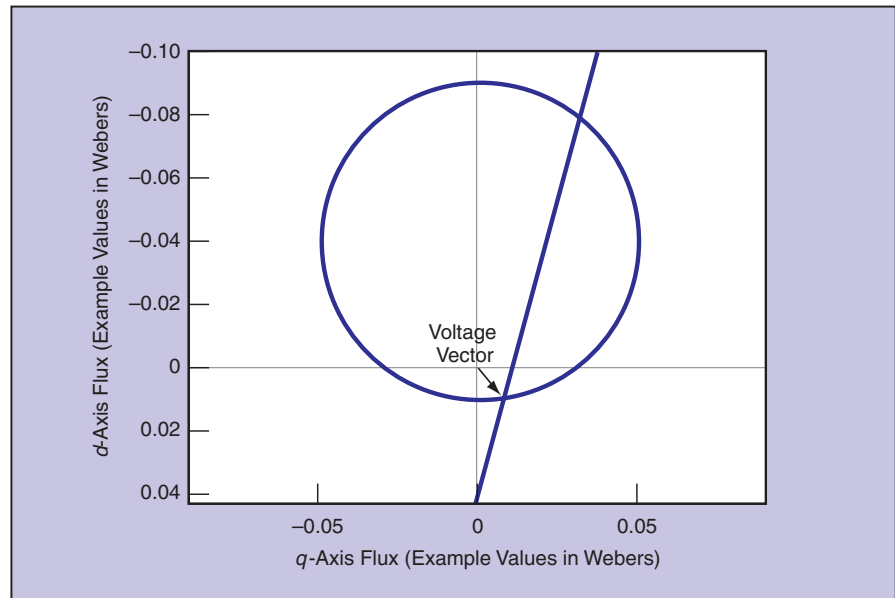
Graphical constructions provide insight into solutions of control problems.

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An improved method and prior methods of deadbeat direct torque control involve the use of pulse-width modulation (PWM) of applied voltages. The prior methods are based on the use of stator flux and stator current as state variables, leading to mathematical solutions of control equations in forms that do not lend themselves to clear visualization of solution spaces. In contrast, the use of rotor and stator fluxes as the state variables in the present improved method lends itself to graphical representations that aid in understanding possible solutions under various operating conditions. In addition, the present improved method incorporates the superposition of high-frequency carrier signals for use in a motor-self-sensing technique for estimating the rotor shaft angle at any speed (including low or even zero speed) without need for additional shaft-angle-measuring sensors.

Prerequisite to a description of the method is a description of the concept of  $dq$  variables and  $dq$  coordinates. The “ $d$ ” and “ $q$ ” signify “direct” and “quadrature,” respectively. The  $dq$  coordinates lie along two orthogonal axes attached to the stator. The  $dq$  coordinates and the  $dq$  variables (which can be, for example, phase voltages and fluxes projected onto the  $dq$  coordinates) are commonly used in the design and analysis of induction motors.

The derivation of the method begins with the observation that a desired change in the torque of an induction motor can be represented as a straight line with units of flux on both axes of the  $dq$  plane. The equation that describes the straight line can be derived from the discrete form of the induction-motor equations by use of the stator and rotor fluxes as state variables. The desired change in stator flux can be represented as a circle on the  $dq$  plane. The voltage needed to achieve the desired change in torque and change in stator flux



A Straight Line and a Circle in the  $d$ - $q$  Plane represent the desired change in torque and the desired change in stator flux, respectively. The voltage vector needed to achieve the desired change in torque and change in stator flux in one time step can be found from one of the intersections of line and the circle.

in one time step can be found from an intersection of the torque line and stator-flux circle (see figure).

Going beyond the aforementioned graphical representations, the maximum-current operating limits can be represented as a set of two lines parallel to the torque line. The maximum-voltage operating limits can be represented as a hexagon on the  $dq$  plane. The maximum-voltage hexagon can be divided into four regions corresponding to an increase or decrease in torque and an increase or decrease in flux. As a result, the effect of a particular voltage vector (increase or decrease in torque or flux) can be clearly seen.

A control algorithm based on the graphical constructions and the underlying equations has been developed. The algorithm causes the synthesis of the needed excitation voltages by use of space vector modulation techniques to calculate and command inverter duty cy-

cles. In the implementation of the algorithm without shaft-angle-measuring sensors, the high-frequency voltage needed for sensorless operation is added to the fundamental voltage and used as input for the PWM calculations. The PWM portion of the control algorithm then determines the duty cycles to generate both voltages at once. The signal from the resulting high-frequency current is processed to estimate the angular position and speed of the rotor.

*This work was done by Barbara H. Kenny of Glenn Research Center and Robert D. Lorenz of the University of Wisconsin. Further information is contained in a TSP (see page 1).*

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